Micro- and macro-elastic properties of tungsten fiber-reinforced tungsten composites probed by nano-indentation and laser ultrasonics

Graduate School of Engineering, Osaka University, Suita, Osaka 565-0877, Japan
* Forschungszentrum Jülich GmbH, Institut für Energie- und Klimaforschung – Plasmaphysik, Partner of the Trieleral Erclescope (TEC), 52425 Jülich, Germany
# Institute of Advanced Energy, Kyoto University, Utsunomiya, Kyoto 611-0011, Japan

10 Max Planck-Instut für Plasmaphysik, 85748 Garching, Germany

Presenter email: ando-si@ist.ist.osaka-u.ac.jp  Corresponding author email: hounlee@iei.eng.osaka-u.ac.jp

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Introduction

Tungsten fiber-reinforced tungsten composites (W/W) are presently being developed in the EU as next generation W materials for plasma-facing components. They possess pseudo-ductility and can overcome some of the limitations caused by the inherent brittleness of pure W. Material properties must be well characterized to allow detailed component design and analysis. The macroscopic mechanical properties of composites depend critically on the microscopic interplay of the matrix, interface, and fiber. If W/W composites are to be used as plasma-facing materials, the effect of hydrogen plasma exposure on the mechanical properties needs to be clarified.

Purpose

To characterize elastic properties of W/W by elucidating the interaction of W-matrix and W-fiber and to investigate the effects of hydrogen inclusion on mechanical properties

Experimental setup

1) Laser ultrasonic method

- Excitation laser (Nd: YAG 1064 nm)
- Beam focused to 1x1 mm diameter
- Pulse repetition rate: 15 Hz
- Needle laser (632 nm)
- Surface displacement ± 75 nm
- Surface velocity up to 3 m/s
- Bandwidth up to 24 MHz

2) Nano-indentation method

- Load Cell
- Indentation load range: 1 mN to 100 mN
- Leaf spring
- Modulus as function of depth

3) W/W composite samples

- W powder grain: 5 μm
- W-fiber length: 2.4 mm
- W-fiber diameter: 0.24 mm
- W-fiber volume fraction: 20% - 60%
- Compared to reference W from ALMT Corp., Japan

Method: Spark Plasma Sintering (SPS)

- Pulsed DC current directly through and heats the graphite die
- High heating or cooling rate enables to sinter metal composites

4) D irradiation experiments

- Irradiation temp: 773 K
- Irradiation time: 100 s
- Fiber volume fraction (%)

Results & Discussion

1) Longitudinal and shear wave velocities from laser ultrasonic

- Data for all 9 measurement spots were averaged
- Wave velocities do not scale with increasing fiber volume fraction
- Wave velocities differ between pure W samples due to density (porosity)
- Poisson's ratio is expressed as a function of C_11/C_12

2) Matrix and fiber modulus from nano-indentation

- Fiber volume fraction (%) is used to determine the modulus of fiber and matrix in each sample
- Each measurement spot was averaged from 1 μm to 1.5 μm

3) Comparison of modulus by two methods as a function of fiber volume fraction in sample

- The average values of fiber modulus between 40% fiber volume fraction sample – suggests that optimum levels for present synthesis method is between 40-50% fiber volume fraction

- Improved bulk elastic properties of W/W composite samples may be possible by increasing matrix strength by using longer fibers

4) Deuterium irradiation effect on elastic properties of W/W composite samples

- There is great variability in the elastic moduli of a single sample depending on location
- To quantify the effects of D irradiation, an attempt was made to examine relative changes in the modulus in a local region separating the irradiated and unirradiated areas (both fiber and matrix)
- Representative data of moduli determined from nano-indentation is shown
- Irradiated and unirradiated areas correspond to red and black lines, respectively
- D irradiation could result in an increase or decrease in the hardness' modulus measurements for both fiber and matrix

Conclusion

- Summary: The purpose of this research was to determine the effect of fiber volume fraction on the elastic properties of W/W samples manufactured using SPS technique. Laser ultrasonic measurements indicate change in bulk modulus between 20-40% fiber volume fraction, while no significant difference was observed between 40-60% fiber volume fraction. To elucidate the dominant contribution on the micro-scale, nano-indentation measurements were performed to measure the strength of fiber and matrix separately.

- Conclusions: Using a simple mixture model considering fiber shortness, we find good agreement between ultra-sonic and nano-indentation measurements – suggesting bulk properties can be described/estimated by linear superposition of micro-scale and matrix strengths scaled by the fiber volume fraction.

- Using the present synthesis method, 40-50% fiber volume fraction is highest Young's modulus due to proper matrix properties at higher fiber volume fraction. Improved synthesis method to increase the matrix strength or using longer fibers may provide a realistic path towards creating stronger W/W composite materials approaching pure-W properties in the elastic regime with the additional benefit of pseudo-ductility.

- Further work required: The effect of D-irradiation on the elastic properties was within the scattering of the data.

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